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San Antonio Veterans Administration Hospital Smoke Movement Study

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Center for Fire Research
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U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, *Secretary*
James A. Baker, III, *Under Secretary*
Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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SAN ANTONIO VETERANS ADMINISTRATION HOSPITAL SMOKE MOVEMENT STUDY

Francis C. W. Fung and Richard H. Zile

A series of full-scale smoke movement experiments was conducted using a sulfur hexa-fluoride (SF_6) gas tracer, smoke simulation system. The experiments were designed to study smoke movement in a hospital building with an interstitial space between floors. The penetration of smoke through ceiling and interstitial space and the vertical smoke movement in such a building were investigated.

Key words: Experiments; full-scale; gas tracer; interstitial space; penetration through ceiling; smoke movement; smoke simulation; sulfur hexa-fluoride (SF_6); Veterans Administration hospital.

1. INTRODUCTION

An entensive series of full-scale smoke movement experiments was conducted using a sulfur hexa-fluoride (SF_6) gas tracer, smoke movement simulation system. The experiment was designed to study systematically the effect of various key variables on smoke movement in the San Antonio Veterans Administration (VA) Hospital. Air from a "burn-room" was mixed with a predetermined percentage of SF_6 tracer gas[1] and heated to a temperature of 5 °C (9 °F) above the corridor temperature. The subsequent spread of tracer gas through the building was monitored.

The hospital has a total of seven floors above grade as shown in figure 1, the elevation sketch. Between each numbered floor there is an interstitial space as shown. The first two floors are divided into six zones labeled A to F as shown in figure 2. The tower portion of the building extends from the third to the seventh floor. Its location in relation to the first two levels is shown in figure 3.

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[1] SF_6 was chosen as a tracer gas because of its electron capture property for detection, as well as being odorless, colorless and stable.

2. EXPERIMENTAL PROCEDURE

In tests 1 to 7 smoke was simulated by the release of the SF_6 tracer gas in a closed room without any forced flow. In tests 8 to 11 smoke was simulated by a net airflow of 19.6-22.4 m^3/min (700-800 ft^3/min) from a room designated as the "burn-room". This pressurized airflow simulated the outflow from a small fire slightly larger than a household fireplace fire. The range of reference concentrations of the SF_6 tracer gas[2] in the air from the burn-room was from 100-150 parts per billion (ppb). Altogether, 11 simulations were tested.

Prior to the beginning of each experiment, the simulated burn-room air was preheated to a temperature of approximately 26.6 °C (80 °F) by an electric heater with a capacity of 1,650 watts. In tests 1 to 7 no fan was used to pressurize the burn-room. For tests 8 to 11 a window box-type fan, installed in the corridor door, was used to force the preheated air from the burn-room into the corridor. A cardboard mask was installed in the corridor doorway to allow air from the burn-room only to be channeled through the fan. The measured airflow through the fan was approximately 19.6-22.4 m^3/min (700-800 ft^3/min) with an average pressure of 1-1.5 N/m^2 (0.04-0.06 inch) water pressure across the fan.

At time zero a standard lecture-size bottle of SF_6 gas located in back of the fan on the room side was turned on to deliver a predetermined amount of SF_6 to be mixed with the burn-room air supply as it passed through the fan. The infiltration of SF_6 gas into the rest of the building was then traced by sampling at designated floors and locations.

3. INSTRUMENTATION

3.1. Flow Rate Measurements

Flow rates across the fan were determined from average velocities. Velocity measurements were performed by using a thermo-anemometer with a low range of 30-150 m/min (100-500 ft/min) and a high range of 150-360 m/min (500-1,200 ft/min). Average velocities were obtained by making a traverse of 9 points across the fan.

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[2] Occupational Safety and Health Administration (OSHA) concentration limits of SF_6 is 1000 ppm as set forth in the Federal Register, Vol. 36, No. 137, August 13, 1971.

3.2. SF_6 Gas Metering

The continuous release of SF_6 gas was metered by a ball-type flow meter with a range of 1.5 to 15 cc/hr (0.05 to 0.5 ft^3/hr. In each test a slight turn of the needle valve unseated the ball to a position registering approximately .3 cc/hr (0.01 ft^3/hr). This range of metering of SF_6, diluted with approximately 22.4 m^3/min (800 ft^3/min) airflow from the burn-room, usually leads to a burn-room SF_6 concentration of the order of 150 ppb. We have found this concentration of SF_6 to be quite acceptable for our experimental requirements since the gas analyzer can detect a concentration of 1 ppb. This means that the relative concentration of SF_6 in relation to the burn-room SF_6 concentration can be measured to one part in one hundred. Additional accuracy of the normalized measurements can be obtained by raising the burn-room SF_6 concentration. However, an increase of burn-room SF_6 concentration leads to a corresponding increase of the purge time between experiments, since the decay of the released SF_6 in the building is exponential with respect to time.

3.3. SF_6 Analysis

SF_6 samples captured by syringes were analyzed by a portable gas chromatograph having an electron capture cell fitted with a 300 mc radiation source. The response of the instrument to SF_6 is exponential and the usable range is between 1 and 1,000 ppb. If dilution of samples was necessary, the usual syringe technique was used.

3.4. Pressure Measurements

Static pressures were measured by a Magnehelic pressure gauge of 0.25 to 12.5 N/m^2 (0.01 to 0.5 in H_2O) range.

4. EXPERIMENTAL RESULTS - TESTS 1 to 7

4.1. Test Conditions of Tests 1 and 2

The objective of these two tests was to evaluate smoke penetration through a ceiling from the burn-room directly to the corridor. Thus, in these two tests the door of the simulated burn-room was closed and the perimeter of the door was sealed off with duct tape. Inside the simulated burn-room an electric heater with a capacity of 1,650 watts was used to raise the room air temperature thus simulating an equivalent small energy fire.

For both tests 1 and 2 the burn-room was Room C153, a patient bedroom (see fig. 4). This room was served by a fan coil unit mounted in the ceiling. A separate air handling unit supplied conditioned outside air at the return duct connecting to each fan coil unit. Exhaust from the room was through a grille located in the connecting toilet room. The exhaust fan duct work serves multiple toilet rooms. Both tests were conducted with fan coil units running, outside supply air unit running and exhaust fan running. The penthouse fans which exhaust air from first floor interstitial space over the burn-room were turned off as a normal operation. Table 1 summarizes the burn-room configurations tested.

4.2. Results of Tests 1 and 2

Results of tests 1 and 2 are shown in tables 2 and 3. In test 1 up to 12 minutes of test time, not a trace of SF_6 was detected in the corridor in front of the burn-room. In test 2 it was decided to take off three ceiling tiles from the burn-room ceiling to simulate an opening above the ceiling. Results of test 2 indicated again, that for up to 10 minutes SF_6 did not directly infiltrate the corridor through the burn-room ceiling. SF_6 was detected in Room C151 (see fig. 4) at 11 minutes. No SF_6 penetrated the ceiling of Room C155 on the other side of the burn-room. (Rooms C151 and C155 are adjacent to the burn-room C153.) Room C151 had a ceiling of acoustical tiles while Room C155 had a plastered ceiling. This indicated that SF_6 did move into the interstitial space through the opening created by the removal of the three ceiling tiles and contaminated Room C151 next door. However, no trace of SF_6 was observed in the corridor.

4.3. Test Conditions of Tests 3 to 7

In view of the findings from the previous two tests, that there was no passage of SF_6 through the burn-room ceiling to corridor, the following tests were planned. The objectives of this series of tests were:

1. To find the extent of involvement of the interstitial space in smoke movement.

2. To find other paths by which smoke could leave the burn-room and infiltrate the rest of the building.

For tests 3 through 7, the burn-room was Room C134, a doctor's examination room (see fig. 4). The room is served from a central air handling unit which has a fixed amount of outside air and return air. The room contains one supply and one return grille. The air handling unit serving this room also serves other rooms as well as adjacent corridors, therefore, any return air picked up from this room or adjacent spaces is recirculated to all spaces. To test the room, the supply and return grilles were taped off according to the schedule shown in table 1, to obtain the desired airflow and room pressure. In all tests, except test 5, the supply and return air handling unit was in operation. Therefore, any smoke which got out of this room could be recirculated through the system to other areas. Except for tests 6 and 7, the interstitial space exhaust fans for the interstitial space over the burn-room were turned off.

4.4. Results of Test 3

In test 3, the burn-room door was sealed off, but both the supply and return air systems were in normal mode and grilles were open. The measuring stations for SF_6 were interstitial space directly above the burn-room and corridor space under the exhaust grille opening which interconnects with the burn-room. At four minutes, a steady SF_6 concentration of 2.3% of burn-room concentration was detected in the corridor. Readings taken in the interstitial space directly above the burn-room showed a gradual increase of SF_6 concentration to 11.3% of the burn-room concentration at 15 minutes. All SF_6 concentrations measured in ppb are tabulated as normalized percent of burn-room concentration and shown in table 3.

4.5. Results of Test 4

In test 4, the basic test 3 configuration was changed by taping off the return air grille in the burn-room. Together with the taped-off burn-room door condition, this allowed the supply fan to pressurize the burn-room. Results of this test, as tabulated in table 5. The measuring stations were again same as test 3. In this case, we noticed a drastic drop in contamination in the corridor, and a substantial increase in contamination in the interstitial space above the burn-room. This is considered to be due to the pressurized burn-room forcing the SF_6 to go through the leaks around the ceiling tiles. Since the return grille in the burn-room was closed off the small amount of SF_6 passage via the exhaust duct could indicate a small amount of leakage into the exhaust duct in the interstitial space. At the end of 10 minutes test time, a steady-state appeared to occur at the two measuring stations.

4.6. Results of Test 5

In test 5, we continued to explore the paths of smoke migration from a room. In this test, the variation from test 4 was that we taped off the supply air grille as well as the return grille. In this case, the measured data indicated that out in the corridor under the communicating corridor return grille opening no contamination of the corridor was detected up to 20 minutes. Contamination of the interstitial space was again noted. However, comparing tests 4 and 5, one finds that the movement of smoke into the interstitial space was more rapid when supply is on and return is taped off (thereby pressurizing the room), and more gradual when both supply and return were taped off. The in-between case is when both supply and return were normal as in test 3.

4.7. Results of Tests 6 and 7

In tests 6 and 7, the condition of a partially burned-out ceiling was simulated. It was decided in test 6 to produce a ceiling opening with a dimension of 0.3 x 0.3 m (1 x 1 ft) in the burn-room. In test 7, three ceiling tiles, each of dimension 0.45 x 0.6 m (1.5 x 2 ft), were removed in the burn-room. This was an attempt to simulate a more severe fire condition. In addition, in both of these two tests, the supply was on and the return was taped off to produce the maximum smoke movement through the ceiling possible with the system. In both tests the interstitial exhaust fans were turned on. Two measuring carts were employed for these tests. One was stationary and one was moving. The stationary cart was located in the corridor in front of the burn-room. Results of test 4, imply that under the above test conditions contamination of the corridor may be insignificant. Thus, it was decided to open a ceiling space 30 x 15 cm (24 x 6 in) right above the stationary instrumentation cart to create an additional passage of connection with the interstitial space. The mobile instrumentation cart was moved to the second level above the fire floor and during the test it was made to traverse the entire second floor. Tables 7 and 8 tabulate the results with the location of the second floor sampling points designated by room numbers and locations.

The concentration readings picked up in the corridor were significantly higher than in the previous tests. This is attributed to the 30 x 15 cm (24 x 6 in) ceiling opening in the corridor that was purposely set up for these 2 tests.

The smoke concentration directly above the burn-room at the second floor passed the 1% level at 14 minutes for test 6 and for test 7 this took place at 10 minutes. Since all variables were the same in these two tests, the larger ceiling opening in the burn-room in test 7 must be taken as the contributing factor in causing faster smoke migration to the second floor.

5. CONCLUSIONS FOR TESTS 1 TO 7

The first 7 tests, were suggested by the VA to investigate smoke penetration from a room to a corridor through a ceiling. It is noteworthy to point out that even with the ceiling open as in tests 6 and 7, it took 10 minutes before smoke penetrated the next level. This time delay in smoke travel is attributed to the interstitial space separating the occupancy levels. Thus, one can conclude that the interstitial space is acting as a smoke sink, particularly if the interstitial space is maintained negative by exhaust fans. This will become more obvious as we describe our vertical smoke movement studies.

In tests 1 to 7, to isolate the ceiling smoke propagation, we taped the door perimeter with duct tape to prevent leakage through the doorway. We then experimented with different ventilation and ceiling opening parameters. Our first seven test results can be concluded as follows:

1. Smoke movement from a room with a sealed door is primarily by leakage through the room's ceiling tiles.

2. Rooms with acoustical tile ceilings permit smoke to penetrate while plastered ceilings are more effective barriers against the penetration of smoke (test 2).

3. Smoke that passed into the interstitial space was diluted and dispersed. Due to the large volume of the interstitial space, it served as an effective smoke sink, particularly if the interstitial space is maintained slightly negative with regards to the spaces below by exhaust fans in the interstitial space.

4. By virtue of the buoyance effect and the storage capacity of the interstitial space, smoke that penetrated through the acoustical tile ceiling did not return and repenetrate the ceiling to contaminate the corridor unless the corridor ceiling was opened up by removing portions of the ceiling tile.

5. For those rooms having a return air connection to the air handling system, the smoke will be picked up from the fire room and rapidly recirculated to the corridor in front of the fire room even though the room door is closed (see results of test 3).

6. Even though the interstitial space acts as an effective smoke sink, the room directly above the fire room may become quickly contaminated with smoke (see results of tests 6 and 7). The mechanism by which smoke penetrates these upper rooms may be via improperly caulked holes (fire stopping) around the plumbing fixtures in these upper rooms. In tests 6 and 7, the exhaust fans for the interstitial space in operation. Even so, the SF_6 penetrated the rooms on the second floor directly over the first-floor fire room in significant amounts. It is possible, if the interstial space fans had a higher capacity, this contamination of the rooms on the second floor may have reduced or eliminated.

6. EXPERIMENTAL RESULTS - TESTS 8 to 11

6.1. Test Conditions of Tests 8 through 11

In tests 8 through 11, the objectives were to simulate smoke movement vertically and horizontally throughout the entire hospital. In these cases, we simulated a burn-room fire and allowed the smoke to leave the burn-room by way of the ceiling as well as the burn-room doorway. To enhance the smoke exit from the doorway, we pressurized the doorway by using a window box-type fan. The doorway was masked throughout except for a cut-out for the fan. This fan generated a flow of approximately 19.6-22.4 m^3/min (700-800 ft^3/min) and a pressure difference of 1-1.5 N/m^2 (0.04 to 0.06 in H_2O). Exact flow and pressure values for each test are tabulated in table 1. The other burn-room test variables are listed also in table 1. Burn-room location and test results are tabulated in tables 9 to 12. For these tests, the two mobile units carrying the SF_6 detector instruments were moved around to obtain time-dependent smoke profiles of the building. Monitoring locations for each measured value are tabulated next to each measurement in tables 9 to 12.

6.2. Results of Test 8

In test 8, the burn-room was located in the first floor Room C134 (see fig. 4). The room air control was in normal mode. The burn-room was heated to 25.6 °C (78 °F) and the doorway pressurized to 1 N/m^2 (0.04 in) H_2O overpressure with an average outflow of 21.6 m^3/min (770 ft^3/min). One instrument cart was located on the first floor and the other was located on the second floor. During the test measurements on the fire floor indications were that smoke was mainly confined to the C wing and E wing (see fig. 2). Up to 19 minutes the out-patient area in A wing had no detectable smoke and the smoke concentration in the D wing at 26 minutes was only 1.6% of burn-room concentration. Due to the locked smoke barrier doors, conditions inside of C wing right above the first floor could not be ascertained. Later tests would give us the chance to evaluate conditions right above the fire floor and on the vertical smoke movement. But results of this test, when compared to tests for other buildings without the interstitial spacing indicated much less horizontal smoke movement in this case. Actually, except for the area immediately surrounding the burn-room, e.g., the C wing, the second floor was smoke-free up to 29 minutes at which time SF_6 began to show up outside of C wing.

6.3. Results of Test 9

In test 9, the burn-room was located on the third floor in Room B318 (see fig. 4). The burn-room air handling operation was in normal mode. The air temperature in the burn-room was raised to 26.7 °C (80 °F) and the burn-room doorway was pressurized to 1.5 N/m^2 (0.06 in) water overpressure with an outflow of 19.2 m^3/min (685 ft^3/min). The objective of this test was to study the vertical smoke movement in the tower. One of the instrument carts was stationed on the third floor and making rounds on that floor for sampling, the other instrument cart was making rounds on the 4th floor and followed the smoke movement to the 5th, 6th and 7th floors later.

A study of the third floor measurements, where the burn-room was located, indicated that the highest smoke readings outside of the burn-room were recorded in B300, the floor dispatch room, and the main elevator shaft. This implies movement of smoke through those shafts. Interesting enough, measurements in stairwells 1 and 2 were quite low indicating little smoke contamination of these two shafts. This phenomenon was confirmed in test 10. It was found in our simulation experiments that smoke will move in limited streams channeled by air handling units and pressure differences caused by vertical shafts. In some cases, it is an obvious situation of smoke taking to the nearest vertical shafts as demonstrated by this and other tests.

Measurements from the upper floors for test 9 are presented in table 10. Examination of the data shows that a small SF_6 trace of between 0.2 to 0.3% of burn-room concentration was detected on the fourth floor area up to 27 minutes. At 28 minutes, the concentration in the intensive care unit directly above the burn-room was only 0.5%. Through the entire test the maximum upper level SF_6 concentration recorded was 1.5% inside stairway 1 at 37 minutes. The next highest reading was 1.4% inside the 6th floor elevator at 55 minutes. Most other floor area measurements during the entire test of 60 minutes were below the 1% level.

6.4. Results of Test 10

Test 10 was, again, conducted with burn-room in Room C318 (see fig. 4). This time a larger airflow of 23.4 m^3/min (835 ft^3/min) was measured across the burn-room doorway. This effectively simulated a larger fire compared to test 9. The burn-room temperature was again raised to 26.7 °C (80 °F). The measurements for test 10, were concentrated to the fire floor, the floor immediately above it and the 6th and 7th floors. A comparison could be made between tests 9 and 10. Generally, it is interesting to note that the trend of both tests were very similar indicating reproducibility of the SF_6 technique.

Measurements from test 10 exhibit a slightly higher reading as expected because of the higher burn-room airflow output. From table 10, it is interesting to note that the SF_6 which infiltrated the vertical shafts did not contaminate the fourth floor at all up to 41 minutes. Instead, the smoke moved on up through the vertical shafts and showed up at 6th and 7th floors. Again, as in test 9, all measurements of SF_6 on the 6th and 7th floor areas were significantly below 1% of the burn-room concentration. The only readings that exceeded 1% were measured either inside vertical dispatch shaft or stairwell and elevators. Figure 5 shows a time history of SF_6 concentration at the sixth floor stairwell and A wing nurse station. The highest stairwell reading at the 6th and 7th floor levels was 1.4%. A 2.1% SF_6 concentration was measured at 7th floor, but that was taken from the vertical floor dispatcher shaft. All the measurements point to below a 1% concentration in all surveyed floor areas except the fire floor. Even in stairwells, all readings were below 1% as in the neighborhood of 1%. Readings above 1% were recorded in the elevator shafts or elevator cabs. These low readings are in contrast to our high-rise smoke simulation experiences encountered with other buildings [1,3].[3]

6.5. Results of Test 11

In test 11, the burn-room was on the first floor in Room C134. The burn-room door was not pressurized by the box fan as in previous tests. Instead the burn-room door was left closed to simulate early fire when the door was still intact. In this case, smoke leakage will be through the door gaps and ventilation openings. This represents a less severe situation compared to tests 8, 9 and 10. The burn-room temperatures

[3] Numbers in brackets refer to the literature references listed at the end of this paper.

were heated up to 26.7 °C (80 °F) and the outside temperature was 15.6 °C (60 °F). The smoke barrier door isolating C wing was closed after starting test. After commencement of testing one instrument cart was stationed on the other side of this smoke barrier door to monitor smoke infiltration from the C wing. The second instrumentation cart was on the second floor making rounds including areas right above the burn-room. Measurements for this test are presented in table 12. On the first floor penetration of smoke across the C wing barrier door was almost immediate. A 1.9% of burn-room concentration was picked up across the smoke barrier door at 3 minutes, at 10 minutes this concentration rose to 23.9%. This buildup of SF_6 concentration across C wing smoke barrier door is presented in figure 6. Elsewhere on the first floor smoke showed up in the E wing and E wing elevator. This was probably due to the recirculation of the smoke by the air handling system as opposed to passage of the smoke through the smoke barrier doors. Away from the fire area, e.g., the F wing and the outpatient area no contamination was recorded (fig. 2). Measurements in the interstitial space above the 1st floor indicated significant contamination. At 64 minutes, interstitial reading of 27.3% was recorded immediately above the burn-room and 12.9% above the C wing away from the burn-room. Despite this intensity of SF_6 in the interstitial space, contamination of the second floor was minimal as shown by values in table 12. At 40 minutes, the second floor maximum SF_6 concentration was only 1.3%. This was taken in the room directly above the burn-room, This seems to confirm again, that the interstitial space did indeed serve as a smoke sink.

7. CONCLUSIONS FOR TESTS 8 to 11

In order to review the results of tests 8 to 10, it is appropriate to discuss our smoke simulation parameters in terms of actual fire parameters, e.g., energy output, gas outflow from a room fire and overpressure buildup by a room fire. For this discussion we shall make extensive use of the formulas derived in [1]. For a detailed derivation of these formulas one can refer to section 2, reference [1].

To recapitulate, for tests 8 to 10, our smoke simulation parameters were 19.6-22.4 m^3/min (700-800 ft^3/min) outflow from the burn-room, 1,650 watts energy input due to the electric heater, and an average overpressure of 1 N/m^2 (0.04 in) water pressure across a 0.6 x 0.6 m (2 x 2 ft) fan. For a ventilation controlled fire in a room, our 19.6 m^3/min (700 ft^3/min) outflow according to formula (10b) in [2] yields a simulated burning rate of 3.6 kg/min (8 lb/min) for a low temperature fire. However, for a high temperature fire, say a burn-room with average temperature 500 °F, our 19.6 m^3/min (700 ft^3/min) will then simulate a burning rate of 1.8 kg/min (4 lb/min). According to formula 12 in [1] the simulated parameter of 1 N/m^2 (0.04 in) water pressure across a 0.6 x 0.6 m (2 x 2 ft) opening can readily match the pressure of a room fire with a burning rate of 1.35 kg/min (3 lb/min).

In a series of ventilation controlled burn-room experiments involving four 18-kg (40 lb) wood cribs conducted at the National Bureau of Standards [2], typical recorded burning rates were 1.35 kg/min (3 lb/min) maximum and 0.9 kg/min (2 lb/min) steady for each vigorously burning crib. Thus, our simulated airflow and overpressure can match 18-kg (40-lb) vigorously burning wood cribs, burning at about 1.35 kg/min (3 lb/min). This leaves the last important simulation parameter, energy output, remaining in question. Taking all into consideration the only feasible way to increase our simulated fire load would be to increase our energy input. Without actually starting a fire the practical limitation would, of course, in this case be the limited current capacity of conventional hospital wiring. Incidentally a 1,650-watt electric heater consumes approximately 15 ampere which is a hefty current in available hospital room wiring. As a result of the present series of experiments, within the range of our simulation parameters, we can make the following conclusions:

1. This series of smoke simulation experiments demonstrated that given a low-order fire in a room where the air from the room is exhausted to the outside and not recirculated, the smoke from the fire will be confined to the room and the interstitial space above the room (see tests 1 and 2 in Room C153). Where the room's air is returned and recirculated through the air handling system, the smoke from the fire in the room will be recirculated to all parts of the building served by the air handling system unless some means are used to isolate the burn-room from the air handling system at the onset of the fire (see tests 8 and 11 for Room C134).

2. Both vertical and horizontal smoke infiltration were not extensive at this hospital compared to similar simulation experiments performed at other high-rise buildings (with the exception of the comments above in 1. relating to the air handling system). However, the tests reported herein were conducted under moderate weather conditions. As a consequence, there was negligible stack effect within the building.

3. Results from experiments 9 and 10 point to the interstitial space as the single factor in smoke infiltration reduction by serving as a smoke absorbing void or "smoke sink."

4. Test 11 shows that smoke barrier doors may not be effective if an air handling system serves areas on both sides of the smoke barrier though it could not be determined how much of the contamination was due to smoke passing through the smoke barrier doors. This points up the necessity of matching the position of smoke barrier partitions and doors with the area covered by the air handling system using recirculated air; or to put it another way, all penetrations through smoke partitions must be protected against the passage of smoke.

5. From the information provided to us, it appears that it is not possible to program the recirculating air handling systems in the VA Hospital, San Antonio, to accomplish area pressurization or exhaust to control the movement of smoke in the hospital. Thus, it would appear that if extensive smoke movement throughout the hospital is to be avoided under fire conditions, something will have to be done to effect shutdown of the recirculating air handling systems in the fire area, either manually or automatically, at the time of the fire emergency. Additionally, the provision of smoke-actuated dampers in these ducts penetrating the smoke barrier partitions may be necessary.

6. It is our understanding that of the seven interstitial spaces in the hospital, only the space over the first floor is provided with positive exhaust. While the interstitial spaces do function as "smoke sinks," their effectiveness could be greatly enhanced if all the interstitial spaces had positive exhaust. Further, their effectiveness could be enhanced even more if the interstitial spaces were provided with large capacity exhaust fans that could be actuated either manually or automatically in the event of fire.

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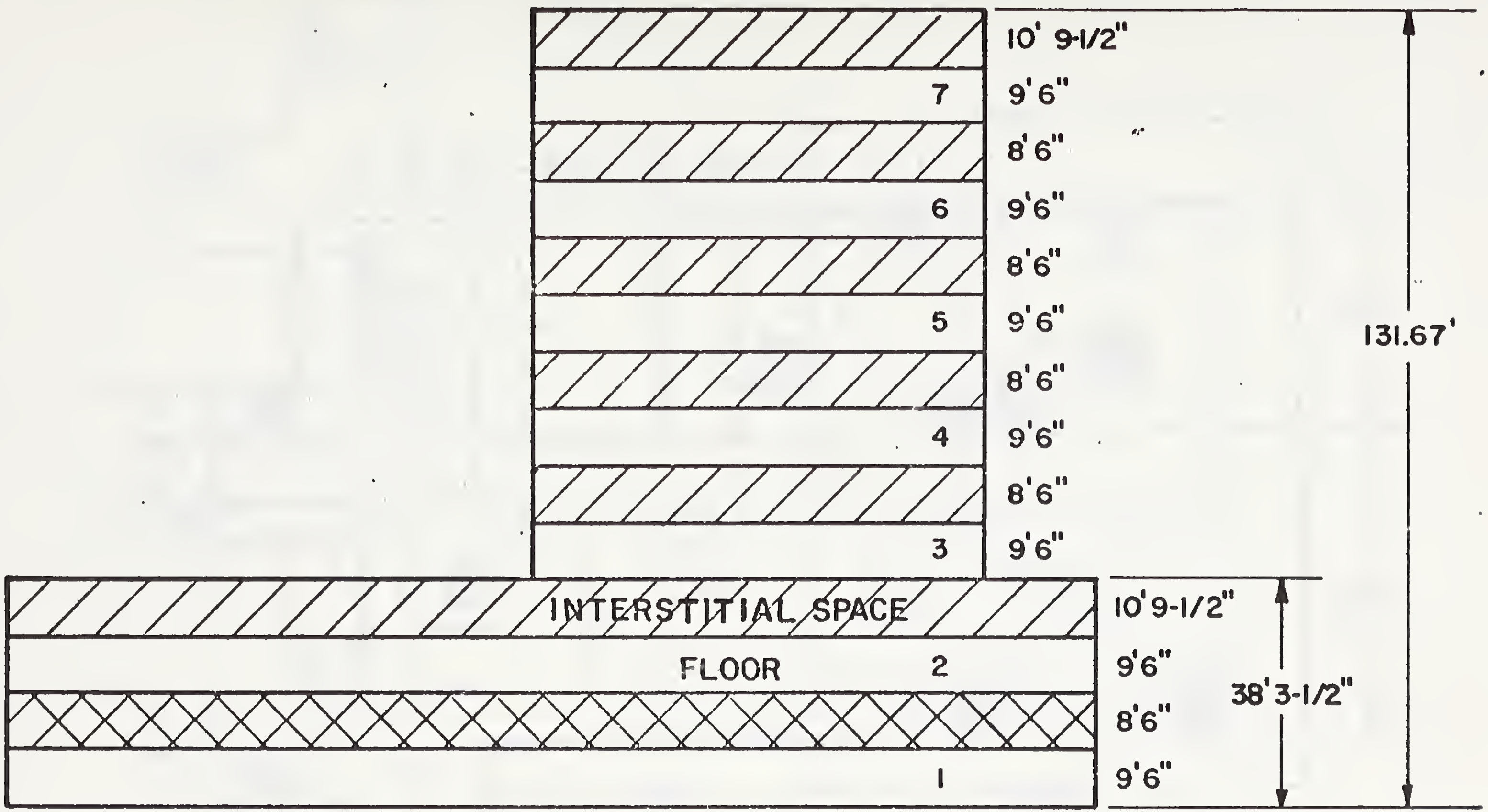

Figure 1. Elevation Sketch, San Antonio Veteran's Administration Hospital (VAH).

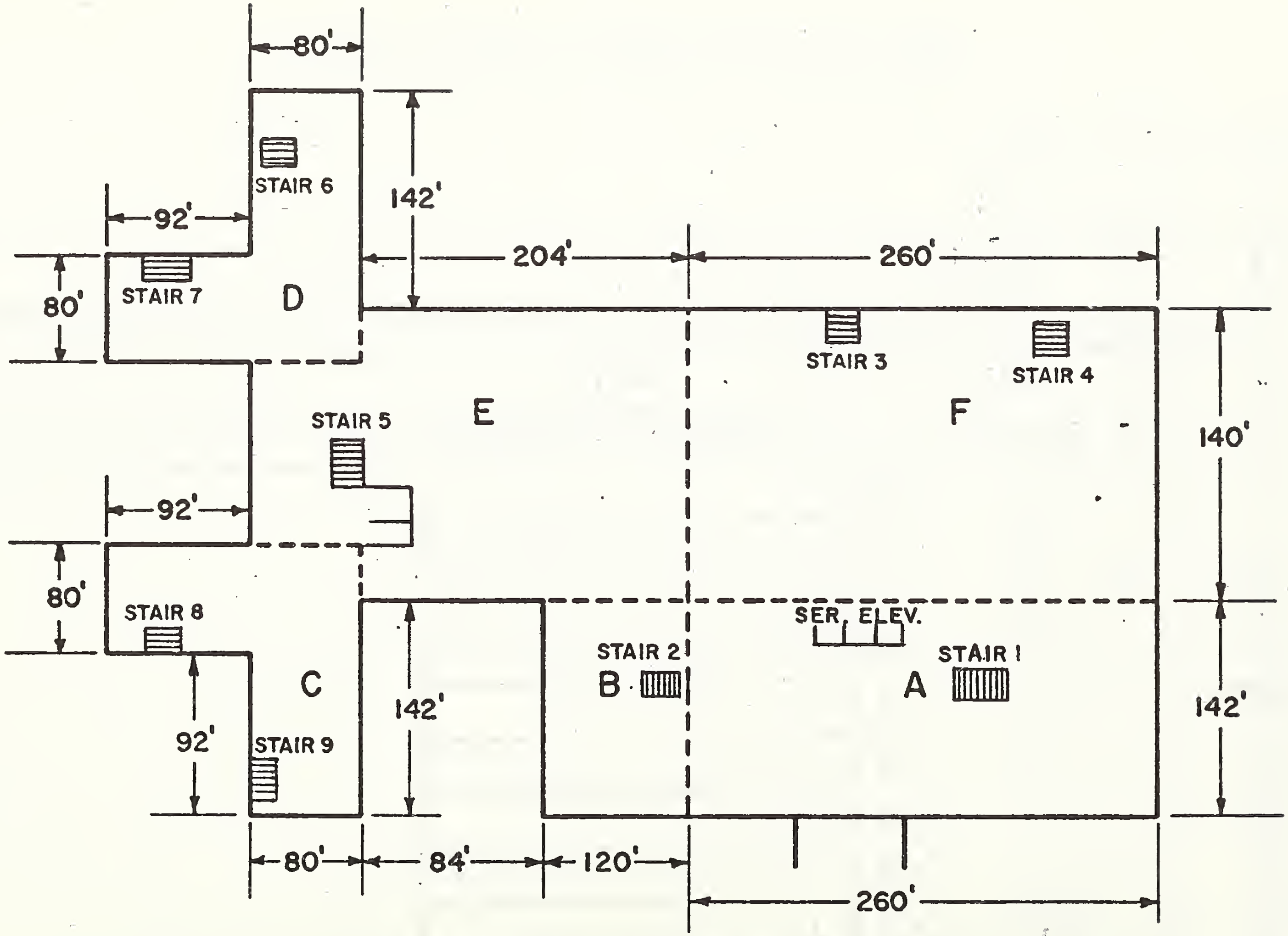

Figure 2. Layout of First Two Floors, VAH.

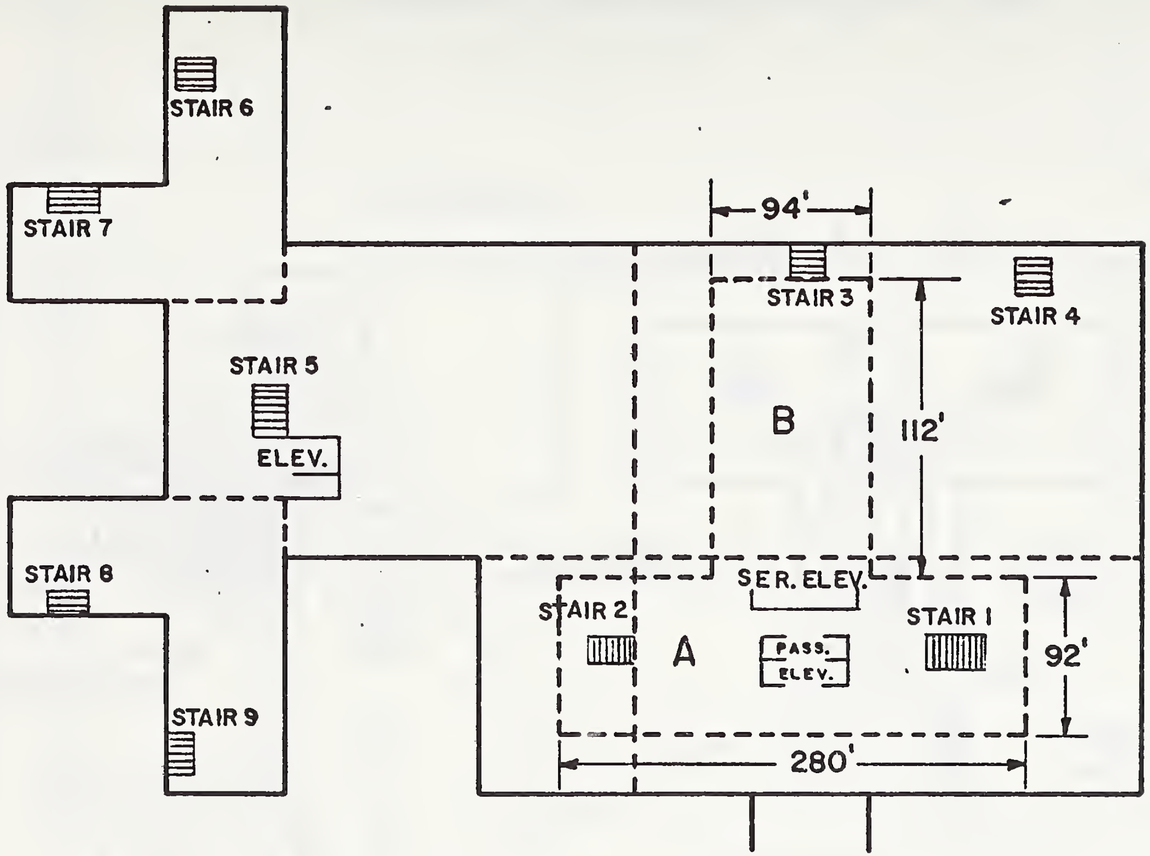

Figure 3. Location of the Tower (3-7 Floors), VAH.

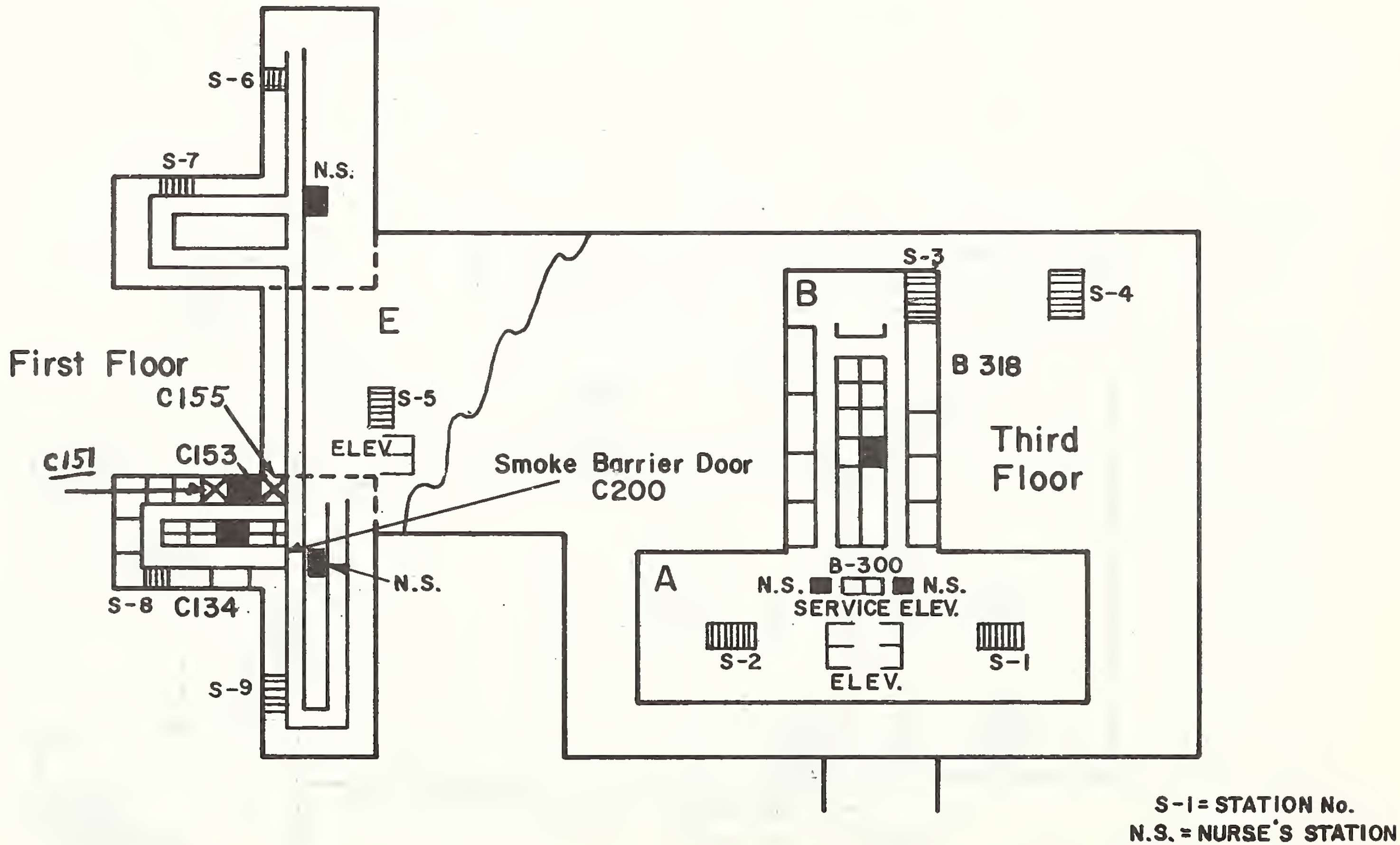

Figure 4. Burn-Room Locations, VAH

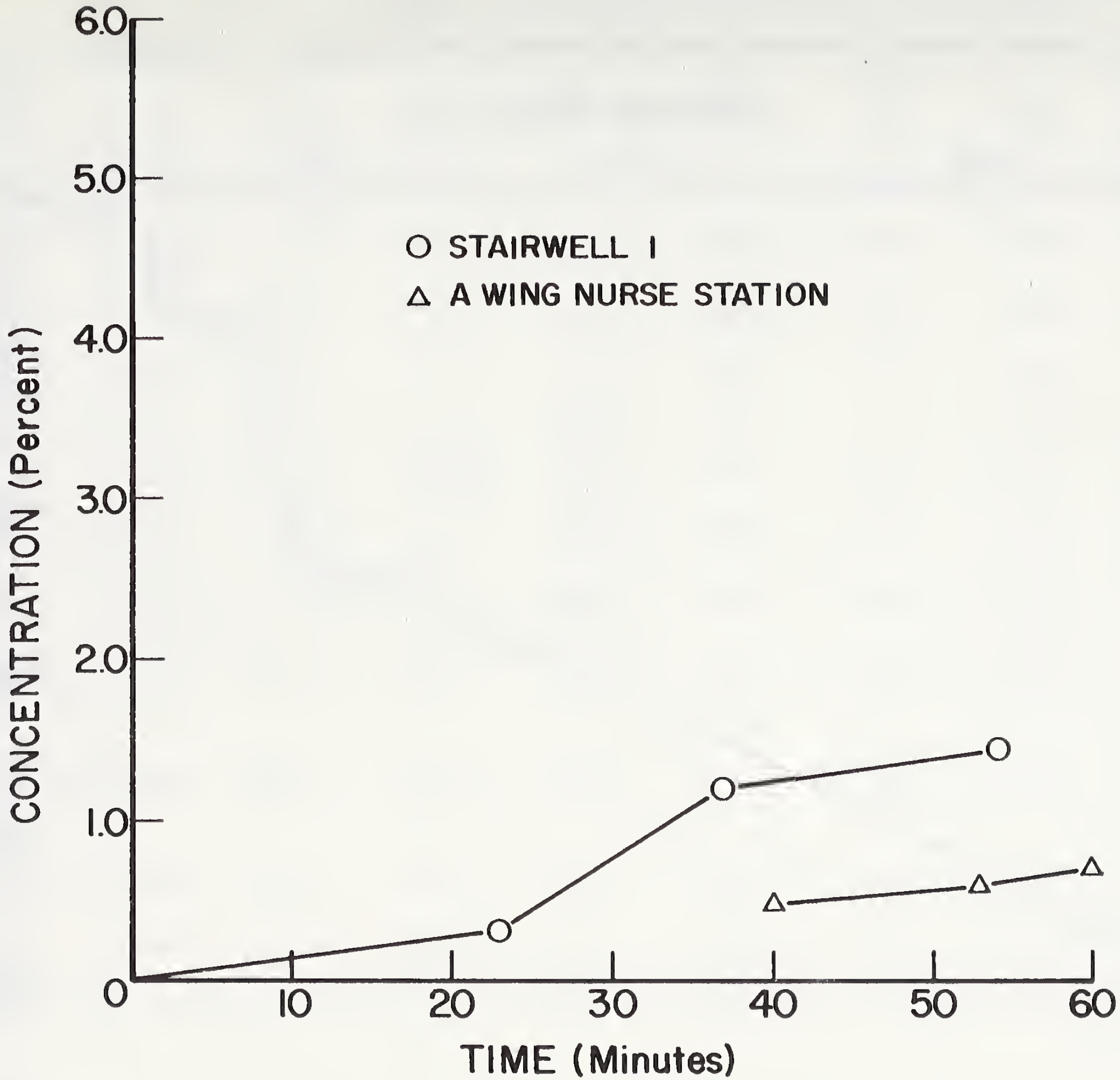

Figure 5. Test 10, Concentration Levels at Sixth Floor.

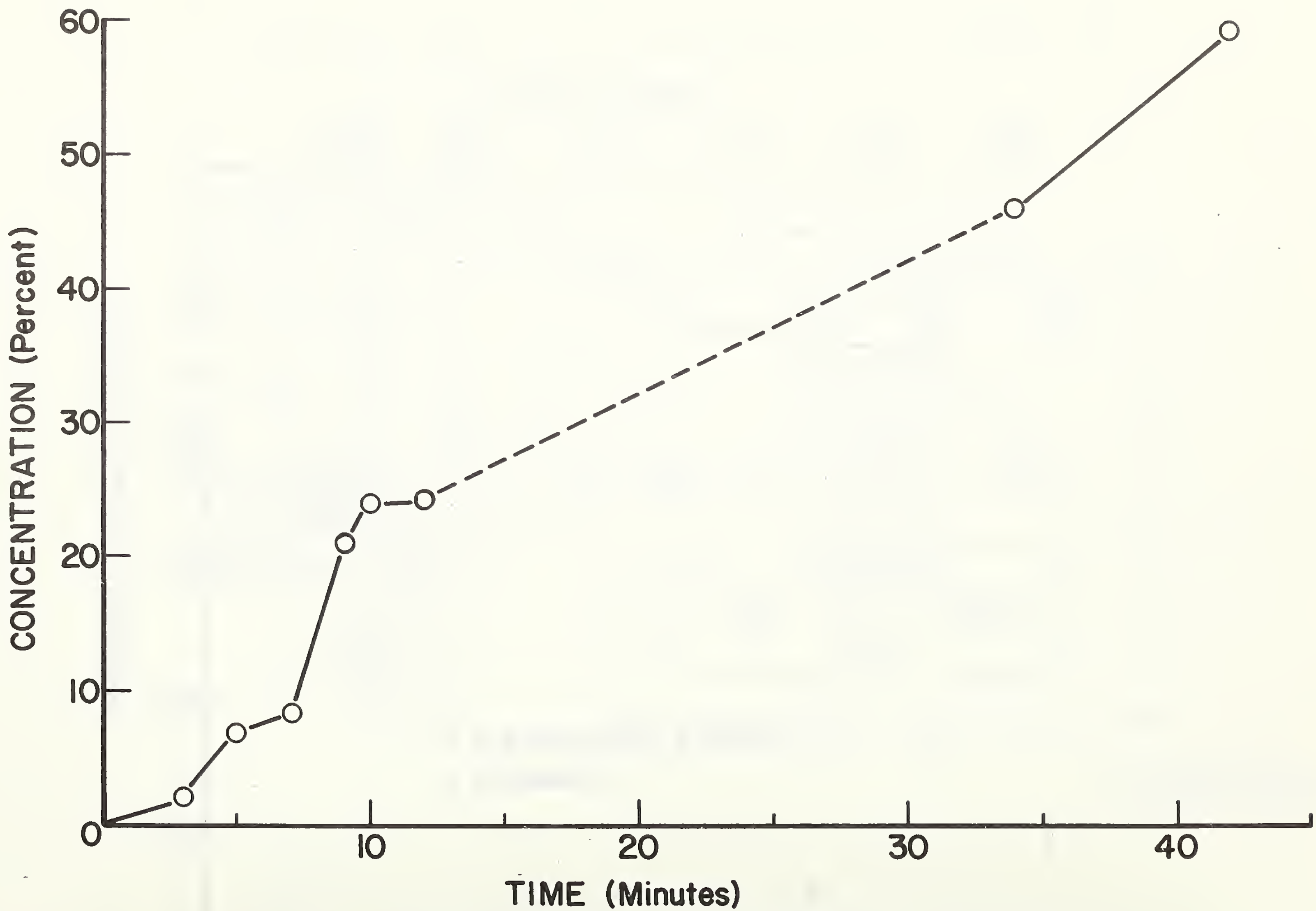

Figure 6. Test 11, Concentration Across C Wing Smoke Barrier Door

Table 1. San Antonio VAH Burn-Room Configurations

Test No.	Burn-Room Door	Ceiling	Door Fan	A/CA Supply	Return/ Exhaust	Room Recir-culation	Inter Conn. Duct	Inters. Fan	Burn-Room Heater	Remarks
1	Sealed C153	Closed	"off"	"on"	"on"	"on"	none	"off"	"on"	
2	Sealed C153	3 tiles "open"	"off"	"on"	"on"	"on"	none	"off"	"on"	
3	Sealed C134	Closed	"off"	"on"	"on"	none	yes	"off"	"on"	
4	Sealed C134	Closed	"off"	"on"	taped off	none	yes	"off"	"on'	
5	Sealed C134	Closed	"off"	taped off	taped off	none	yes	"off"	"on'	Supply fan
6	Sealed C134	1'x1' open	"off"	"on"	taped off	none	yes	"on"	"on'	Corridor ceiling 6"x24" opening
7	Sealed C134	Open 3 tiles	"off"	"on"	taped off	none	yes	"on"	"on'	Corridor ceiling 6"x24" opening
8	Pressurized doorway C134	Closed	"on"	"on"	"on"	none	yes	"on"	"on'	770 cfm op=.04"H_2O Airflow from across B.R. pressurized B.R. door
9	Pressurized doorway B138	Closed	"on"	"on"	"on"	none	yes	"on"	"on"	685 cfm op=.06"H_2O Airflow from across B.R. Pressurized B.R. door
10	Pressurized doorway B318	Closed	"on"	"on"	"on"	none	yes	"on"	"on"	835 cfm op=.05"H_2O Airflow across B.R. pressurized B.R. door
11	Closed C134	Closed	"off"	"on"	"on"	none	yes	"on"	"on"	

Table 2. San Antonio VAH Smoke Simulation Test 1

Location	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location	Time min	Concent ppb	Percent of Burn-Room	Remarks
Corridor in	0	0	0		Corridor in	7	0	0	
	1	0	0			8	0	0	
front of	2	0	0		front of	9	0	0	
	3	0	0			10	0	0	
	4	0	0			11	0	0	
burn-room	5	0	0		burn-room	12	0	0	

Test Data

Burn-Room Location: C153
Burn-Room Concentration: 155 ppb

Temperature, Outside: 78 °F
Inside: 75 °F*
Burn-Room: 75 °F

*Room A/C Defeats
B.R. source heater

Table 3. San Antonio VAH Smoke Simulation on Test 2

Location	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location	Time min	Concent ppb	Percent of Burn-Room	Remarks
Corridor in	0	0	0		Corridor in	7	0	0	
front of	1	0	0		front of	8	0	0	
Burn-Room	2	0	0		Burn-Room	9	0	0	
" "	3	0	0		" "	10	0	0	
" "	4	0	0		Room C151	11	6.8	4.4	
" "	5	0	0		Room C155	16	0	0	Plaster ceiling
" "	6	0	0						

<u>Test Data</u>

Burn-Room Location: C153
Burn-Room Concentration: 155 ppb

Temperatures, Outside: 75 °F
Inside 74 °F*
Burn-Room: 74 °F

*Room A/C Defeats B. R. Source Heater

Table 4. San Antonio VAH Smoke Simulation Test 3

Location	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location	Time min	Concent ppb	Percent of Burn-Room	Remarks
	0	0	0			0	0	0	
Corridor adj.	1	0	0		Interstitial	1	0	0	
	2	0	0			2	0	0	
to	3	0	0			3	0	0	
	4	3.7	2.3		space	4	3.1	1.9	
exhaust	5	3.7	2.3			5	1.2	.7	
	6	3.7	2.3			6	1.9	1.1	
near	7	3.7	2.3		above	7	6.2	3.7	
	8	3.7	2.3			8	6.2	3.7	
	9	3.7	2.3			9	6.3	3.7	
burn-room	10	3.7	2.3			10	10.5	6.6	
						12	10.0	6.5	
					burn-room	13	16	10	
						15	18	11.3	

Test Data

Burn-Room Location: C134
Burn-Room Concentration: 160 ppb
Burn-Room over pressure: .01" H_2O before sealing door

Temperature, Outside: 75 °F
Inside: 74 °F
Burn-Room: 79 °F

Table 5. San Antonio VAH Smoke Simulation Test 4

Location	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location	Time min	Concent ppb	Percent of Burn-Room	Remarks
	0	0	0			0	0	0	
	1	0	0			1	21	10.5	
Corridor Adj.	2	0	0		Interstitial	2	65	32.5	
	3	0	0			3	91	45.5	
	4	0	0			4	90	45	
to Exhaust	5	0.3	.15		space above	5	118	59	
	6	0.3	.15			6	126	63	
	7	08	.4			7	142	71	
Near	8	08	.4		Burn-Room	8	142	71	
	9	1.24	.6			9	142	71	
Burn-Room	10	1.24	.6			10	142	71	

Test Data

Burn-Room Location: C134
Burn-Room Concentration: 198 ppb

Temperatures, Outside: 75 °F
Inside: 74 °F
Burn-Room: 80 °F

Table 6. San Antonio VAH Smoke Simulation Test 5

Location	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location	Time min	Concent ppb	Percent of Burn-Room	Remarks
	0	0	0			0	0	0	
	1	0	0			1	0	0	
Corridor Adj.	2	0	0		Interstitial	2	0	0	
	3	0	0			3	0	0	
	4	0	0			4	0	0	
to Exhaust	5	0	0		space above	5	0	0	
	6	0	0			6	0	0	
	7	0	0			7	0	0	
Near	8	0	0		Burn-Room	8	0	0	
	9	0	0			9	0	0	
	10	0	0			10	1.8	1.2	
Burn-Room	11	0	0			11	1.8	1.2	
	12	0	0			12	1.8	1.2	
	13	0	0			13	1.8	1.2	
	14	0	0			14	1.9	1.2	
	15	0	0			15	1.6	1.1	
	16	0	0			16	6.2	4.1	
	17	0	0			17	3.1	2.1	
	18	0	0			18	4.8	3.2	
	19	0	0			19	9.9	6.6	
	20	0	0			20	22.3	14.9	

Test Data

Burn-Room Location: C134
Burn-Room Concentration: 150 ppb

Temperature, Outside: 60 °F
Inside: 73 °F
Burn-Room: 75-81 °F

Table 7. San Antonio VAH Smoke Simulation Test 6

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks
	0	0	0		C234	0	0	0	
	1	0	0		"	1	0	0	
Corridor under	2	0	0		"	2	0	0	
	3	0	0		"	3	0	0	
	4	0	0		"	4	0	0	
	5	0	0		–	–	–	–	
ceiling opening	6	4.3	2.9		C244	6	0	0	
	7	4.3	2.9		–	–	–	–	
	8	5.0	3.3		C250	8	0	0	
	9	5.0	3.3		E226	9	0	0	
in front of	10	5.0	3.3		–	–	–	–	
	11	6.2	4.2		Stairwell 5	11	0	0	
	12	5.6	3.8		–	–	–	–	
	13	5.9	4.0		–	–	–	–	
Burn-Room	14	5.0	3.3		C234	14	1.8	1.2	
	15	–	–		C244	15	1.8	1.2	
	16	6.1	4.1		C250	16	2.4	1.6	
	17	–	–		C234	17	7.8	5.2	
	18	8.4	5.6		–	–	–	–	
	19	–	–		C244	19	1.8	1.2	
	20	15.0	10.0		C250	20	5.4	3.6	
					C234	22	11.5	7.9	

*Floor location see figure 4.

Test Data

Burn-Room Location: C134
Burn-Room Concentration: 148.8 ppb

Temperature, Outside: 70 °F
Inside: 73 °F
Burn-Room: 80 °F

Table 8. San Antonio VAH Smoke Simulation Test 7

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks
	0	0	0		C234	0	0	0	
Corridor under	1	0	0		"	1	0	0	
	2	0	0		"	2	0	0	
	3	0	0		"	3	0	0	
ceiling opening	4	.6	4		"	4	0	0	
	5	.6	4		"	5	0	0	
	6	1.9	1.2		C234	6	.5	.3	
	7	-	-		C244	7	.4	.3	
in front of	8	1.2	.8		C234	8	-	-	
	9	-	-		"	9	.6	.4	
	10	1.3	.9		"	10	2.2	1.5	
	11	1.3	.9		"	11	2.5	1.7	
Burn-Room	12	1.9	1.2		"	12	2.5	1.7	
↓	13	-	-		"	13	2.5	1.7	
	14	2.5	1.7		"	14	3.8	2.6	
	15	-	-		"	15	3.8	2.6	
	16	2.5	1.7		"	16	3.8	2.6	
	17	3.1	2.1		"	17	3.8	2.6	
	18	3.1	2.1		"	18	4.3	2.9	
	19	2.5	1.7		"	19	5.8	3.9	
	20	3.2	2.2	SF_6 shut-off	"	20	6.5	4.4	
					C244	22	8.6	5.8	
					C250	23	12.3	8.3	
					C234	24	12.0	8.1	
					C244	25	13.0	8.7	
					C250	26	13.8	9.3	
					C244	27	13.8	9.3	
					"	28	13.7	9.2	
					"	29	13.7	9.2	
					"	30	15.4	10.3	
					C244	31	16.1	10.8	
					Elevator	33	-	-	
					Stairwell 5	34	0	0	

*Floor location see figure 4.

Test Data

Burn-Room Location: C134
Burn-Room Concentration: 148.8 ppb

Temperature, Outside: 70 °F
Inside: 73 °F
Burn-Room: 80 °F

Table 9. San Antonio VAH Smoke Simulation Test 8

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location*	Time No.	Concent ppb	Percent of Burn-Room	Remarks
E wing elevator	5	0	0		In front of	1	0	0	
A wing elevator	8	0	0		C200 smoke door	2	0	0	
Outpatient	10	0	0		away from fire	3	0	0	
F wing	14	0	0		" " "				
Stair 4	16	0	0		" " "				
Outpatient	19	0	0		" " "	29	.6	.5	
F wing elevator	23	14.6	12.4		" " "	31	.6	.5	
Stair 5	24	9.4	8.0		" " "	38	3.2	2.7	
D wing	26	1.9	1.6		" " "	40	3.0	2.6	
C nurse station.	31	49.5	42						
C nurse station	35	49.5	42		C200 smoke barrier door locked				
C nurse station	37	54.6	46.3		Cannot gain entrance into second				
C nurse station	40	65.1	55.3		Floor area immediate above first				
Burn-Room	42	117.8	100		Floor burn-room area.				

*Floor location - see figure 4.

Test Data

Burn-Room Location: C134
Airflow: 770 cfm
Over Pressure: .04"H_2O

Burn-Room Concentration: 117.8 ppb

Temperature, Outside: 69 °F
Inside: 74 °F
Burn-Room: 78 °F

Table 10. San Antonio VAH Smoke Simulation Test 9

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks
A wing nurse	1	0	0		B422	4	0	0	
Station	2	0	0		A407	7	0	0	
Station	4	0	0		A419	9	0	0	
Main elevator	6	10.1	6.7		A400 Elevator	11	0	0	Floor dispatch
B300	7	74.4	49.7	Floor Dispatch	B420	12	0.4	0.3	
Stairwell 3	10	0	0		Intensive care	15	0	0	Over burn-room
A wing nurse station	12	17.9	11.9		B411	17	0	0	
A wing nurse station	14	17.9	11.9		B420	18	0.3	0.2	
Stairwell 1	16	0.9	0.6		A400 Elevator	20	0.4	0.3	
Stairwell 1	18	0.9	0.6						
Stairwell 1	20	0.9	0.6		A407	25	0.4	0.3	
Stairwell 1	22	2.8	1.9		B420	27	0.3	0.2	
Stairwell 1	24	2.8	1.9		Intensive care	28	0.8	0.5	
Stairwell 1	28	2.8	1.9		B411	30	1.0	0.7	
Stairwell 1	30	2.8	1.9		B400	32	1.9	1.3	
A wing nurse station	32	18.6	12.3		A407	33	0.6	0.4	
A wing nurse station	34	26.7	17.7		A419	35	0.4	0.3	
Main Elevator	36	74.4	49.4		Stairwell 1	37	2.3	1.5	
Stairwell 2	38	0.9	0.6		A400 Elevator	38	2.0	1.3	
Stairwell 2	44	1.0	0.7		B420	40	0.6	0.4	
Stairwell 2	50	1.0	0.7		B411	41	1.7	1.1	
A wing nurse station	54	21.1	14.0		Stairwell 3	45	1.6	1.1	
Main elevator	55	82.5	54.7		5th floor elevator	48	1.8	1.2	
B300	56	86.5	57.4		B517	51	0.5	0.3	
Burn-Room	57	150.7	100						
					6th floor elevator	55	2.1	1.4	
					B602	57	0.6	0.4	
					B712	61	0.8	0.5	

*Floor location - see figure 4.

Test Data

Burn-Room Location: B318
Airflow: 685 cfm
Over Pressure: 06"H_2O

Burn-Room Concentration: 150.7 ppb

Temperature, Outside: 74 °F
Inside: 75 °F
Burn-Room: 80 °F

Table 11. San Antonio VAH Smoke Simulation Test 10

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks
3+ A wing nurse station	7	0	0	Nurse station
" Stairwell 1	10	0	0	
" Elevator	12	5.6	5.2	
" A wing nurse station	14	0	0	
" B300	20	43.0	39.6	Floor dispatch
" A wing nurse station	21	9.4	8.7	
" Stairwell 1	25	.6	.5	
" Elevator	27	13.5	12.4	
" A wing nurse station	32	23.4	21.6	
" Stairwell 1	33	2.7	2.5	
" A wing nurse station	42	22.1	20.4	
" B300	44	74.4	68.6	Floor dispatch
" A wing nurse station	47	15.4	14.2	
4+ Stairwell 1	15	0	0	
" B400	17	0	0	Floor dispatch
" Elevator	19	0	0	
" A wing nurse station	28	0	0	Nurse station
" Stairwell 1	29	0	0	
" Elevator	30	1.7	1.6	
" A wing nurse station	38	0	0	
" Stairwell 1	39	.6	.6	
" Elevator	41	1.4	1.3	

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks
6+ Elevator	10	0	0	
" Stairwell	11	0	0	
" A600	21	0.8	0.7	Elevator
" A607	22	0	0	Nurse station
Stairwell 1	23	0.3	0.3	
6+ Elevator	25	0.9	0.8	
" A660	35	1.2	1.1	
" 607	36	0.7	0.7	
" Stairwell 1	37	1.3	1.2	
" 607 Nurse station	40	.5	.5	Nurse station
" A600	41	1.7	1.6	
" Elevator	43	6.5	6.0	
" A660	52	3.5	3.2	
" 607 Nurse station	53	.6	.6	Nurse station
" Stairwell	54	1.5	1.4	
" 607 Nurse station	60	.8	.7	Nurse station
7+ 707 Nurse station	15	0	0	Nurse station
" Stairwell 1	16	0	0	
" 707 Nurse station	20	0	0	
" A700	30	1.0	0.9	Floor dispatch
" A707 Nurse station	31	0	0	
" A700	44	2.3	2.1	Floor dispatch
" 707 Nurse station	45	0.3	0.3	
" Stairwell 1	46	1.0	0.9	
" 707 Nurse station	50	0.2	0.2	
" 700 Nurse station	51	1.4	1.3	Floor dispatch

*Floor location see figure 4.

+Numbers indicate floor level.

Test Data

Burn-Room Location: B318
Airflow: 834 cfm
Over Pressure: .05" H_2O

Burn-Room Concentration: 108.5 ppb

Temperatures, Outside: 65 °F
Inside: 72 °F
Burn-Room: 80 °F

Table 12. San Antonio VAH Smoke Simulation Test 11

Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks	Location*	Time min	Concent ppb	Percent of Burn-Room	Remarks
C wing across smoke door	3	2.3	1.9	Across smoke door	C234	5	0	0	
C wing across smoke door	5	8.2	6.9		E226	10	0	0	
C wing across smoke door	7	9.9	8.3		B219	16	0	0	
C wing across smoke door	9	24.9	20.9		A201	18	0	0	
C wing across smoke door	10	28.5	23.9		Stairwell	23	0	0	
C wing across smoke door	12	28.5	23.9		A200	24	0	0	
E127 elevator	14	14.3	12.0		E226	31	0.57	0.47	
Main elevator	16	0	0		C250	33	0.81	0.7	
Out patient	18	0	0		C234	40	1.5	1.3	
Section F	20	0	0		E226	42	1.6	1.3	
Section F	22	0	0		A200	45	0.0	0.0	
Out patient	26	0	0		Stairwell 3	48	0.0	0.0	
Out patient	28	0	0		E213	52	0.0	0.0	
Out patient	30	0	0		C250	55	1.9	1.6	
E127 elevator	32	21.6	18.2		C234	56	3.1	1.8	Above burn-room
C wing across smoke door	34	5.5	46.2		Interstitial Burn-room	64	32.5	27.3	
Out patient	38	0	0						
Out patient	40	0	0						
C wing across smoke door	42	70.1	58.8						
E127 elevator	48	21.6	18.2						
Out patient	50	0	0						
Out patient	52	0	0						
Interstitial Above C wing	65	15.5	12.9						

*Floor location see figure 4.

Test Data

Burn-Room Location: C134
Forced Airflow: fan off, Heater on
Over Pressure: negligible

Burn-Room Concentration: 119.04 ppb

Temperatures, Outside: 60 °F
Inside: 73 °F
Burn-Room: 80 °F

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A series of full-scale smoke movement experiments was conducted using a sulfur hexa-fluoride (SF_6) gas tracer, smoke simulation system. The experiments were designed to study smoke movement in a hospital building with an interstitial space between floors. The penetration of smoke through ceiling and interstitial space and the vertical smoke movement in such a building were investigated.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Experiments; full-scale; gas tracer; interstitial space; penetration through ceiling; smoke movement; smoke simulation; sulfur hexa-fluoride (SF_6); Veterans Administration hospital.

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